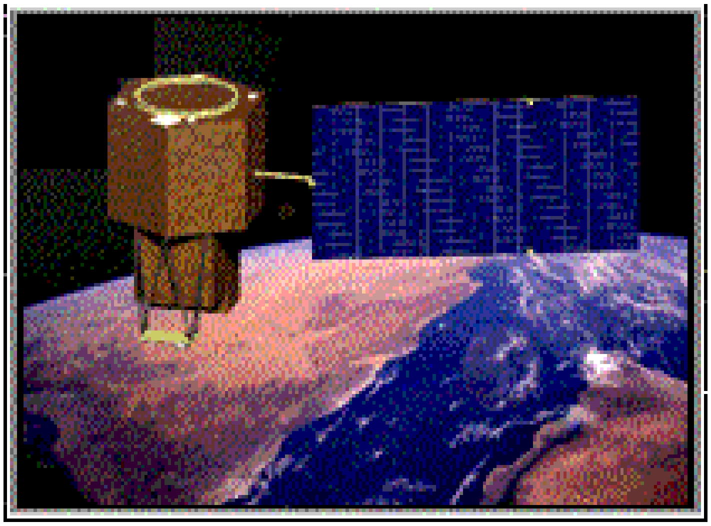

NMP / E0-1 VALIDATION PLAN
ENHANCED FORMATION FLYING

by
Goddard Space Flight Center
JPL
Stanford

4/30/97

Preface

This document is under the configuration management of the Flight Dynamics Division (FDD) Earth Observing -1 (EO-1) Enhanced Formation Flying (EFF) Team. Change requests to this document shall be submitted to the EO-1 EFF team, and changes shall be implemented following concurrence of the EFF team. The current document will be maintained in an on-line library.

Questions concerning this document and proposed changes shall be addressed to:

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1.0 TECHNOLOGY NAME:

Autonomous Navigation and Control of Formation Flying Spacecraft

2.0 SPONSORSHIP:

ADT Lead:Robert Connerton/GSFC

2.1 SPONSORING IPDT:

Autonomy

2.2 TEAM MEMBERS:

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3.0 OVERVIEW

This plan focuses on the validation of the core AutoCon flight control architecture required to support Enhanced Formation Flying (EFF) during the extended EO-1 mission. The Autocon flight code will reside in the EO-1 onboard computer and interface through the ACS. AutoCon is being developed and unit tested by GSFC codes 550 and 712 along with Stanford University. This effort will be accomplished in several AutoCon builds which will be integrated into the EO-1 ACS build-3. AutoCon will be unit and system tested based on simulations using a ground system version of AutoCon prior to integration with the ACS. The validation of the software will be performed in multiple phases with each phase meeting a specific objective as described in section 6.0 below. The Prelaunch verification of these algorithms will be performed in the software test facility and will require interfaces to the ACS for command and telemetry and to the GPS hardware for state vector data. The validation of the AutoCon flight code will be completed in coordination with the ACS testing and its integration into the spacecraft.

3.1 EO-1 FORMATION FLYING REQUIREMENTS

The formation flying requirement of EO-1 is to maintain a 1-minute separation between EO-1 and Landsat-7 with EO-1 following the Landsat-7 ground track to a tolerance of +/- 3 km tolerance, approximately 6 (tbd) seconds. This translates into an along-track distance of approximately 450 km with tolerance of 50 km. The mapping of this requirement into a formation flying requirement is to place a constraint on the initial separation between the two spacecraft, and maintaining that separation. Using the formation flying algorithms developed by GSFC and JPL, simulations have shown that formation flying requirements can be easily met by a wide margin. By performing this spacecraft separation maintenance, pair scene comparisons between Landsat-7 and E0-1 can be made.

4.0 INTRODUCTION

The primary objective of enhanced formation flying is to demonstrate onboard autonomous formation flying control of the EO-1 spacecraft with respect to the Landsat-7 spacecraft. A secondary goal is to enable the collection of correlated science measurements and to demonstrate significantly improved space science data return through near-simultaneous observations. The AutoCon flight control architecture is modular and accommodates Goddard and Jet Propulsion Laboratory formation flying algorithms, along with algorithms from several industry partners, under a single architecture. All algorithms must conform to AutoCon specifications in order to allow uploading during the extended mission. Individual algorithms are invoked through ground commanding of an AutoCon control mode switch. The enhanced formation flying technology demonstration will be fully validated during the EO-1 extended mission. In this way, science taken during the first year without onboard formation flying control can be compared to science collected during onboard formation flying control to determine the improvement. Likewise, operations costs with and without onboard formation flying control can also be compared.

The core AutoCon flight control architecture required to support all enhanced formation flying (EFF) algorithms during the extended EO-1 mission will be developed, integrated with the ACS, and placed onboard the spacecraft prior to the EO-1 launch in May 1999. Validation of the core AutoCon architecture will occur during the first year of EO-1 operations. The core AutoCon flight control software must be integrated with the ACS and the spacecraft prior to launch to reduce the risk and the amount of software being uploaded later in the mission. Formation flying control algorithms will be uploaded and executed under the AutoCon flight control software during the extended mission.

5.0 TECHNOLOGY DESCRIPTION

Spacecraft with multiple scientific payloads often present competing/conflicting requirements on spacecraft design and operation. Separating scientific payloads onto several single-string spacecraft can accomplish the same complex missions without the added design and operational overhead, while risking only one payload at a time. The proposed approach for onboard formation flying control will enable a large number of spacecraft to be managed autonomously and with a minimum of ground support. The technology will enable group of spacecraft to detect errors and cooperatively agree on the appropriate maneuver to maintain the desired positions and orientations.

The sensitivity of scientific instruments can often be increased by expanding the effective observation baselines, which can be achieved by distributing the scientific payloads on many separate spacecraft. However, data collection will impose quite stringent requirements on the Real-Time cooperation between these spacecraft to react to disturbances such as environmental forces. The technologies proposed herein for formation flying spacecraft will eventually make these missions routine and cost effective. Formation flying will also play a key role in the development of future orbiting very long baseline interferometers (Origins program), and allow the establishment of multiple spacecraft arrays for the coincident collection/calibration of instrument data required for future Earth science.

This joint technology features flight software that is capable of autonomously planning, executing, and calibrating routine spacecraft orbital maneuvers. A ground-based prototype using fuzzy logic has already been developed by GSFC (Code 550) for the TRMM and SAIL/UFO missions to demonstrate the viability of automated orbit control. The autonomous formation flying control software in this proposal will build on this existing capability for the maneuver planning, calibration, and evaluation tasks. The fuzzy control engine will be ideal for this function because it can easily handle conflicting constraints between spacecraft subsystems.

The AutoCon flight control system will need data from additional sensors and spacecraft subsystems such as propulsion data, ground track data, and navigation and attitude data. It will then be possible to autonomously generate, analyze, and execute the maneuvers required to initialize and maintain the vehicle formation. Because these calculations and decisions can be performed onboard the spacecraft, the lengthy period of ground-based planning, currently required prior to maneuver execution, will be eliminated. The proposed system will also be modular so that it can be easily extended to future missions. Furthermore, the AutoCon flight control system is designed to be compatible with various onboard navigation systems (*i.e.* GPS, ONS, or an uploaded ground-based ephemeris). The existing automated maneuver planning tool (AutoCon) will be modified for onboard autonomous formation flying control to demonstrate that improved science data return can be achieved by correlating nearly simultaneous data. This will be accomplished by having the flight control system plan a maneuver that places EO-1 within 1 minute of separation from Landsat-7 and then maintains that separation to a tight tolerance of 10 seconds for an extended period of time.

6.0 TECHNICAL VALIDATION OBJECTIVES

The EO-1 software test validation certifies that all software requirements have been properly implemented and that Phase-1 of the Enhanced Formation Flying (EFF) software meets all operational objectives.. This section summarizes the approach used to accomplish these goals.

The core AutoCon flight control software will be qualified by executing a series of test plans, test data, and test scenarios. The results of each stage of validation will be checked and documented. These activities have inputs from both the developers of AutoCon and the EO-1 ACS software engineers. Quality assurance will be integrated into each stage.

The qualification of the processes that will be used to monitor validation are by; analysis, inspection, test, and demonstration. The requirements by which the test will show qualification are by ACS external interfaces, functional, sizing, timing, and tractability.

The validation of each of these tests will be performed at the following levels. Please note that Level 1-4 are the verification process required to support Level-5 validation of AutoCon.

- Level-1: AutoCon, using a PC or workstation environment to develop, test, provide high fidelity simulations, and proof of concept fuzzy logic rules.
- Level-2: Virtual Simulation, using a virtual simulation of the ACS with an embedded AutoCon core architecture flight code design to test the interfaces, telemetry, and commands with the ACS.
- Level-3: Software Test Facility, using a full spacecraft simulation of the ACS and GPS data to test AutoCon. Test all interfaces to the ACS and C&DH for telemetry and commanding. Performed on a Mongoose breadboard with supporting hardware.
- Level-4: Flatsat, testing of the AutoCon flight code on flight hardware and ACS system software.
- Level-5: Operational testing/validation of the core AutoCon flight code. These tests are expected to require a minimum amount testing to verify proper execution of the AutoCon flight control system.

To minimize associated test costs associated with these tests, the following approach is recommended.

- For each functional requirement develop scenarios that will be executed for the mission.
- Develop system test for each scenario
- Develop system unit, integration tests for EO-1 AutoCon to develop a system checkout matrix
- Perform system tests for the mission scenarios and catalog results in matrix

The EO-1 maneuvers will be computed onboard under a single system architecture called AutoCon which employs separate maneuver decision/design modules or algorithms. AutoCon will control execution of the modules through an onboard mode switch, and perform constraint evaluation via fuzzy logic control. The AutoCon specifications will be levied on the industry partners in order to facilitate uploading algorithms during the extended mission. Data and processing requirements from industry partners will be assessed during this initial phase of the technology.

6.1 AUTOCON EXECUTIVE AND FUZZY LOGIC VALIDATION

Validation of the Build-1 of core AutoCon architecture executive will be performed during the first year of the EO-1 mission. This build is the system level control of all of the enhanced formation flying algorithms. The objective is to test the fuzzy logic control and the development of the fuzzy logic engines. The test will ensure that the input, output, CPU memory, storage, processing speed requirements and the interface to the ACS provided data performs as expected and that control will be invoke at the proper time for maneuver algorithms.

6.1.1 Required data/necessary measurements:

The data required to validate AutoCon in Phase-1 are listed below from reference 1 (the AutoCon / ACS ICD). Fuzzy logic and fuzzy rule sets are the primary data requirements. Secondary data requirements are real data sets of EO-1 position state vectors from the EO-1 GPS orbit determination solutions and the Landsat-7 state vectors from the uplink of these vectors. The ACS provides data in memory locations for input to the fuzzy logic control. Output files for placement into the interface with the ACS for telemetry will be exercised.

CCSDS Header				EO-1 Mass			CCSDS Packet Header (include s/c Id ?)
EFF UTC Time (MET of current EFF Cycle + UTCF)				EO-1 Coefficient of Drag			ACS UTC Time (MET of current ACE 8 Hz Pkt Hdr + UTCF)
Heartbeat Cycle Count				EO-1 Coefficient of reflectivity			EO-1 ACS X-Position Vector
Autocon Cycle Count				EO-1 Drag Area			EO-1 ACS Y-Position Vector
WARM Restart Cnt				EO-1 SRP Area			EO-1 ACS Z-Position Vector
EFF Burns Planned							EO-1 ACS X-Velocity Vector
EFF Planned Burns Implemented				LS-7 Mass			EO-1 ACS Y-Velocity Vector
EFF Planned Burns Loaded				LS-7 Coefficient of Drag			EO-1 ACS Z-Velocity Vector
EFF Planned Burns Executed				LS-7 Coefficient of reflectivity			Valid EO-1 ACS
EFF Planned Burns Aborted				LS-7 Drag Area			EO-1 ACS State Source Status -- sometjing ???
ACS TLM Pkt Received Cnt				LS-7 SRP Area			EO-1 GPS SPS State Epoch
GPS TLM Pkt Received Cnt							EO-1 GPS SPS X-Position Vector
RCS TLM Pkt				F10.7			EO-1 GPS SPS Y-

Received Cnt								Position Vector
					KP			EO-1 GPS SPS Z-Position Vector
SCRIPTS - Free Flowinf Text								EO-1 GPS SPS X-Velocity Vector
Along Track Tolerance Fuzzy Set								EO-1 GPS SPS Y-Velocity Vector
Radial Tolerance Fuzzy Set								EO-1 GPS SPS Z-Velocity Vector
Fuzzy Set								Valid EO-1 GPS SPS
								EO-1 GPS GEODE State Epoch
LS-7 State Epoch								EO-1 GPS GEODE Y-Position Vector
LS-7 State X-Position Vector								EO-1 GPS GEODE Z-Position Vector
LS-7 State Y-Position Vector								EO-1 GPS GEODE X-Velocity Vector
LS-7 State Z-Position Vector								EO-1 GPS GEODE Y-Velocity Vector
LS-7 State X-Velocity Vector								EO-1 GPS GEODE Z-Velocity Vector
LS-7 State Y-Velocity Vector								Valid EO-1 GPS GEODE
LS-7 State Z-Velocity Vector								EO-1 GPS WAAS State Epoch
								EO-1 GPS WAAS Y-Position Vector
								EO-1 GPS WAAS Z-Position Vector
								EO-1 GPS WAAS X-Velocity Vector
								EO-1 GPS WAAS Y-Velocity Vector
								EO-1 GPS WAAS Z-Velocity Vector
								Valid EO-1 GPS WAAS
								Mission Phase
								ACS Mode

Table 6-1

6.1.2 Approach:

The validation approach is to execute AutoCon onboard with these input data values listed in Table 6-1 and allow Autocon to process the data using the fuzzy logic control algorithms. These algorithms will both notify the ACS and ground through telemetry of a maneuver and in phase-2 invoke the maneuver planning algorithms within AutoCon. The validation will show that the fuzzy logic properly resolves conflicting constraints; that AutoCon can ingest the data from the ACS correctly for internal use; and that the interfaces with the ACS for all telemetry and command is working correctly. The final result of the phase-1 validation is that the telemetry output confirms the maneuver decision has selected a proper time for a maneuver. Also, the validation will prove the interface to AutoCon via

ACS uplinked tables functions properly and confirm the required memory sizing of the onboard computer.

6.1.3 Anticipated Results:

The anticipated results are that AutoCon returns a maneuver required flag and related information for the planning of the maneuver. There should not be any interface errors. The AutoCon software should run within the tolerance specified for the memory requirements and timing requirements of the onboard computer. The validation will verify the AutoCon interface to the ACS. An analysis of the downlinked telemetry will show the data provided though memory to the AutoCon system and the execution of the high level AutoCon system in terms of fuzzy logic, system control limits and flags was as expected. An indication by AutoCon that the data for the maneuver algorithms has been generated and control passed to the correct maneuver process is expected. The results anticipated are the data within the telemetry data packets match the ground generated data. The differences between the ground and onboard AutoCon are expected to meet the values due only to difference in the software (constrained software run times or precision) and hardware (PC based versus Flight hardware). Scenarios for the validation will address each difference.

6.1.4 Supporting I&T Data

Supporting I&T data of propulsion data, health and safety data, and other constraint data uplinked for AutoCon control will be required. The input data will include preloaded fuzzy rule set and constraint checking limits. The validation requires that these data be commandable for a complete checkout of this algorithm. The validation will require software and hardware used for independent checking of orbital data, the use of the ground operational version of AutoCon for the validation of the fuzzy logic and rules, and the use of the Hammers Co.'s VirtualSat software for checking of all interfaces and the associated timing requirements.

Table 6-2 Supporting I&T Hardware and Software

Data Validated	Software	Hardware
Orbital Data	Swingby	PC
Interface Checkout	VirtualSAT	PC/Windows-NT
AutoCon-Ground	AutoCon	PC/Windows-NT
Telemetry Data	Telemetry Processor	EO-1 Control Center H/W

6.1.5 Rationale:

The reasoning for this validation is to test the control methodology of the AutoCon executive through the processing of the fuzzy logic rules and the fuzzy logic engines. The difference expected are discussed above are to be minimal and only due to implementation in the spacecraft specified hardware software.

7.0 SCIENTIFIC VALIDATION OBJECTIVES

The enhanced formation flying will demonstrate the capability of EO-1 to fly over the same ground track as Landsat-7 within 3km at the equator. This requirement allows images to be taken for the project's paired scene comparison science requirements. The validation will prove the correctness of the onboard algorithms for autonomous control.

8.0 SCHEDULES

Two schedules are listed below. One for the overall development and support of the validation of AutoCon, and the other which shows the schedule of activities for the validation.

The overall AutoCon schedule includes the development, integration, pre-launch testing, and on-orbit validation of the core architecture (Table 1). It should be noted that all the software will be unit and system tested at the Flight Dynamics Facility before the integration into the ACS build-3.

Table -1 Master Schedule

Name	Start	Finish
EO-1 Launch	5/1/99	5/1/99
ACS Build 1	11/1/96	4/30/97
ACS Build 2	4/1/97	12/31/97
ACS Build 3	12/1/97	4/1/98
Autocon Baseline System	7/15/96	6/20/97
Formation Flying Specifications	10/1/96	5/1/97
Simulation Development	11/1/96	5/1/97
Build 1 Design	4/1/97	5/15/97
Build 1 Implimentation	5/15/97	7/15/97
Build 1 Test	7/15/97	8/15/97
Build 2 Design and Implimentation	7/15/97	8/15/97
Build 2 Test	8/15/97	9/15/97
Build 3 Design and Implimentation	8/15/97	9/15/97
Build 3 Test	9/15/97	10/15/97
Build 4 Design and Implimentation	9/15/97	10/15/97
Build 4 Test	10/15/97	11/15/97
Build 5 Design and Implimentation	10/15/97	11/15/97
Build 5 Test	11/15/97	12/15/97
Flight S/W Architecture	12/1/96	12/15/97
Deliver Build 5 to Hammers	12/15/97	12/15/97
Integrate & Test w/ ACS	9/15/97	12/15/97
Acceptance Test	12/15/97	4/15/98
S/C IV&V	7/1/98	5/1/99
FlatSAT Testing	5/18/98	7/31/98
Validation Plan Draft	12/1/96	2/28/97
Validation Plan Final	2/28/97	4/30/97
Test Plan	4/1/97	8/1/97
Phase C/D Confirmation Review	5/6/97	5/7/97
AutoCon PDR	5/14/97	5/14/97

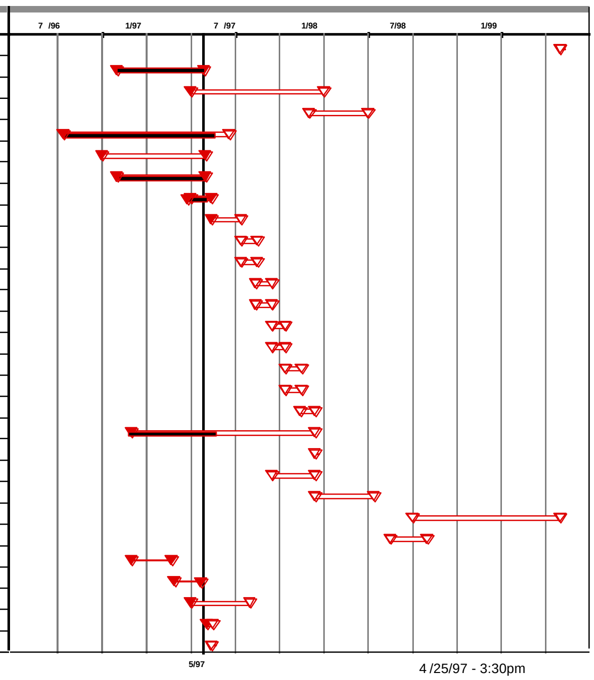

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Table - 2 Validation Schedule

ID	Task Name	Duration
1	AutoCon Power-up	0.1d
2	AutCon Staus Validation	1d
3	Telemetry Downloads	11.7d
12	Table Uploads	13.6d
20	Validation of Interfaces	0.5d
21	Validation of Data Ingest	0.5d
22	Validation of Fuzzy Rules	2.88d
23	Validation of Fuzzy Logic	1.5d
24	Validation of Constraint Check	0.5d
25	Validation of Timing and CPU	0.5d
26	Comparison with Swingby	0.5d
27	Comparion With Gnd AutoCOI	0.5d
28	Comparison with Virtual Sat	0.5d
29		
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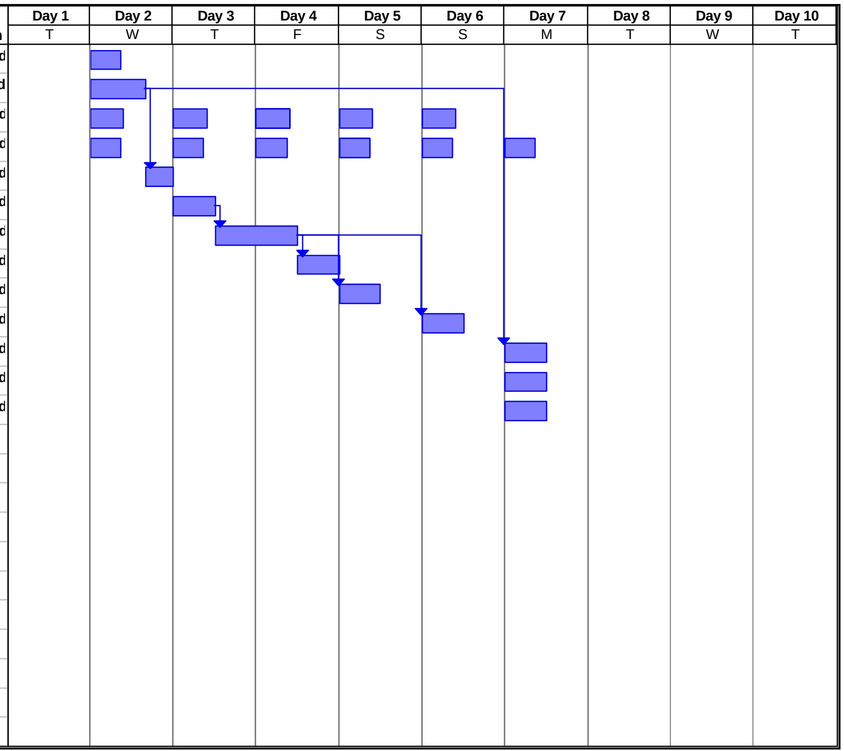

9.0 REQUIRED MANPOWER

Table 2 shows the estimated civil service manpower for the Goddard Space Flight Center. These numbers are FTEs. JPL input: assuming a validation period of 12 months, the required JPL workforce is 0.7 workyears.

Table 2 Civil Servant Staff Resources (550/712)

AUTOCON (Enhanced Formation Flying Executive)
Validation of AUTOCON Executive
Validation of AUTOCON Fuzzy Logic Engines
On-orbit checkout

Skill	**Code**		**FY97**	**FY98**	**FY99**	**FY00**	
Co-investigator		**550**		**0.1**	**0.1**	**0.1**	**0.1**
Lead EFF engineer	**550**		**0.3**	**0.3**	**0.3**	**0.3**	
Lead software engineer		**550**		**0.2**	**0.3**	**0.2**	**0.2**
Lead investigator	**712**		**0.1**	**0.1**	**0.1**	**0.1**	
Assist EFF engineer	**712**		**0.1**	**0.1**	**0.2**	**0.1**	
Assist software engineer		**712**		**0.2**	**0.2**	**0.1**	**0.1**
Totals			**1.0**	**1.0**	**1.0**	**0.9**	

10.0 REQUIRED FACILITIES

The EFF software requires both an independent set and a common set of test tools, equipment, and facilities which are also being developed for the EO-1 ACS testing, and GPS testing. The facility is the Virtual Sat facility of the Hammers Co. It will be required to validate the AutoCon onboard algorithms as they interface with the onboard ACS flight code. A ground-based version of the AutoCon system within VituralSat will allow full integration and test of the complete system of all fuzzy logic algorithms as they are developed. It is anticipated that the flight code validation tests will yield the same results are the ground tests.

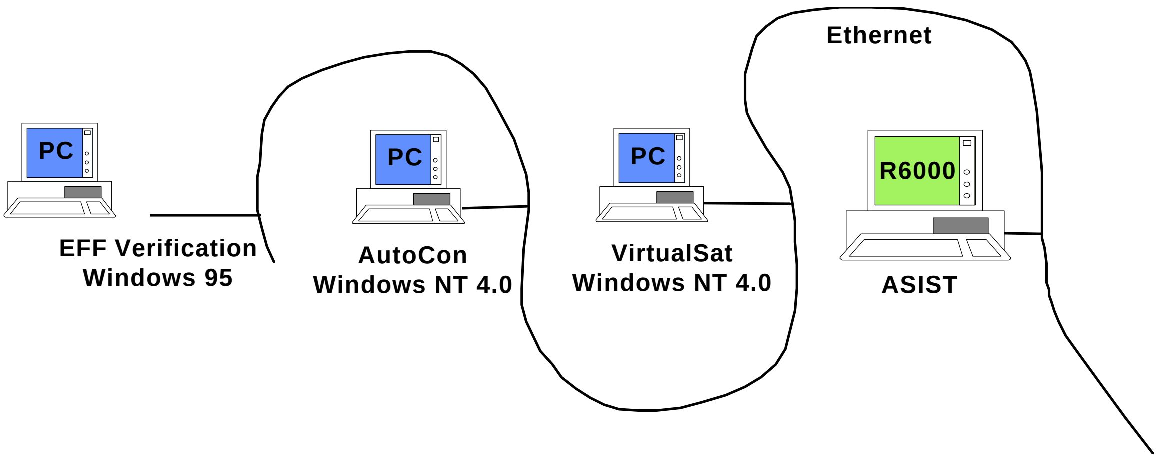

Figure 1. Virtual Sat Facility